AIAA's Aircraft Technology, Integration, and Operations (ATIO) 2002 Technical
1-3 October 2002, Los Angeles, California

AIAA 2002-5825

DISTRIBUTED AIR/GROUND TRAFFIC MANAGEMENT – TECHNOLOGY AND CONCEPT DEMONSTRATION REPORT

Vernol Battiste[1], Walter Johnson[1], Parimal Kopardekar[2], Sandra Lozito[1], Richard Mogford[1], Everett Palmer[1], Thomas Prevot[3], Nicole Sacco[2], Stephen Shelden[3], and Nancy Smith[1].
[1]NASA Ames Research Center, Moffett Field, CA
[2]Titan Systems, Mays Landing, NJ
[3]San Jose State University, CA

ABSTRACT

A technology and concept demonstration was conducted to evaluate three NASA Advanced Air Transportation Technologies Office, Distributed Air/Ground Traffic Management (DAG-TM) Concept Elements – En Route Free Maneuvering, En Route Trajectory Negotiation, and Terminal Arrival Self-Spacing – in a virtual operating environment that included controllers, pilots, and simulation support personnel. The test made use of three facilities – the Airspace Operations Laboratory, Flight Deck Display Research Laboratory, and Crew Vehicle Systems Research Facility's Advanced Concepts Flight Simulator (ACFS) – along with an array of existing and concept-specific decision support tools (DSTs) and procedures. Participant controllers monitored and then transitioned free flight aircraft into controlled airspace, data-linked route and clearance information, and sequenced aircraft for approach and landing using NASA DSTs. Pilot participants flew the ACFS, solved route conflicts in free flight airspace, data-linked route changes to air traffic controllers for approval, and spaced on a lead aircraft during the approach phase using an enhanced Cockpit Display of Traffic Information. Traffic density varied from light to heavy across four scenario types. The demonstration indicated that the DAG-TM concepts should be explored for their potential to increase NAS flexibility and capacity. The test environment was proven to be a robust and useful infrastructure for more advanced research in the future. The participant feedback provided valuable insight into the continued development of DSTs and procedures that will help guide the direction and refinement of future research.

Background

NASA's Distributed Air/Ground Traffic Management (DAG-TM) research represents a paradigm shift that may bring change to the roles and responsibilities of air traffic service providers (ATSPs), traffic flow management (TFM) specialists, flight crews (FCs), and Airline Operations Center (AOC) dispatchers. The DAG-TM vision comprises 15 Concept Elements (CEs) covering all phases of flight. The CEs were designed to address specific inefficiencies in the National Airspace System. DAG-TM research is being carried out at the NASA Ames, Glenn and Langley research centers. The current research priorities include: CE 5, En Route Free Maneuvering; CE 6, En Route Trajectory Negotiation; and CE 11, Terminal Arrival Self-Spacing. [1] (The work reported on here represents only a part of the NASA DAG-TM research activities being undertaken, and the specific procedures described are subject to change and refinement as the work matures.)

In CE 5, *En Route Free Maneuvering*, appropriately equipped aircraft in en route airspace accept the responsibility to maintain separation from other aircraft, while exercising the authority to freely maneuver to fly a user-preferred trajectory that conforms to active local traffic flow management (TFM) constraints. Free maneuvering aircraft have the authority to make trajectory changes with the restriction that no new conflicts are created within a defined period of future flight time. Free maneuvering aircraft have flight deck decision support tools (DSTs) that enhance situation awareness, allow FCs to maintain separation from other aircraft without ATSP assistance, and provide route replanning capabilities. [2]

CE 6, *En Route Trajectory Negotiation*, supports interaction among the DAG-TM stakeholders (pilots, ATSP, and AOC) when a trajectory change is initiated in response to local TFM constraints. During trajectory negotiation, the role of the ATSP is to define the operating constraints and to retain full responsibility for separation assurance. The pilot's role is make informed requests that avoid conflicts with other aircraft or airborne hazards (e.g., special use airspace or weather), precisely follow the negotiated FMS flight path, and meet the ATSP's imposed traffic constraints. In CE 6, the AOC defines airline constraints and preferences (related to fuel efficiency, scheduling, or passenger comfort) that may be considered in the trajectory negotiation.

The communication and negotiation inherent in CE 6 helps ensure that all stakeholder requirements are considered. Trajectory changes may be initiated by any of the stakeholders, but ultimate responsibility for separation remains with the ATSP. [3]

In CE 11, *Terminal Arrival: Self-Spacing for Merging and In-Trail Separation*, equipped aircraft self-merge into an arrival stream and maintain an ATSP-specified, in-trail separation from a designated lead aircraft. FCs receive traffic intent data via a cockpit situation display, and airborne DSTs aid them in performing merging and spacing operations. Use of this concept is expected to increase terminal area throughput by providing pilots and controllers with a reliable method for closing the gap between arriving flights. The time-based, rather than distance-based, algorithm employed allows for spacing compression as aircraft speeds decrease. [4]

Demonstration Objectives

The goals of the September 2001 NASA Ames DAG-TM demonstration were to provide for initial instantiation of the necessary simulation technology, and to conduct a preliminary assessment of the feasibility and benefits of CE 5, CE 6, and CE 11. The specific objectives were to:

1. Identify procedural, automation, and human factors considerations related to free maneuvering.
2. Identify procedural, automation, and human factors considerations related to transitioning between free maneuvering and controlled airspace.
3. Identify conflict management issues related to free maneuvering and trajectory negotiation.
4. Identify procedural, automation, and human factors considerations related to self-spacing.
5. Examine the role of the ATSP within CE 5, CE 6, and CE 11.
6. Examine the role of the FC within CE 5, CE 6, and CE 11.
7. Examine the communication needs between the FC and ATSP within CE 5, CE 6, and CE 11.

Method

Participants

Four controllers participated in the study. Two en route controllers attended from Oakland Air Route Traffic Control Center (ARTCC), and the two terminal controllers were from Bay Terminal Radar Approach Control (TRACON).

Two commercial airline pilots participated, flying the Advanced Concepts Flight Simulator (ACFS). Pseudo pilots operated all other simulation aircraft.

Flight Scenarios

The demonstration made use of six unique traffic scenarios: Two were for equipment, concept, and procedure training, and there were four test scenarios including CE 5 Light, CE 5 Heavy, CE 6 Light, and CE 6 Heavy – the qualifier in each case referring to the associated traffic density. All scenarios involved both en route and terminal airspace operations. The CE 5 scenarios used CE 5 procedures in en route airspace and CE 11 procedures in the terminal airspace. The CE 6 scenarios used CE 6 procedures in en route airspace and CE 11 procedures in terminal airspace (see Operational Rules below). In all scenarios, aircraft in free flight were transitioned to ATSP control while in en route airspace (that is, prior to entering terminal airspace).

Airspace Environment

The airspace environment was the Dallas Fort Worth ARTCC (ZFW) and TRACON areas – specifically super high, high altitude, and TRACON arrival sectors.

Assumptions

The following sub-sections detail assumptions related to DST use, procedures, roles, and responsibilities.

DST Related Assumptions

1. All aircraft were datalink equipped, had a Cockpit Display of Traffic Information (CDTI) incorporating conflict alerting logic, and a Flight Management System (FMS).[5] In-trail spacing was accomplished using an airborne inter-arrival spacing tool developed by NASA Langley Research Center.[6]
2. Aircraft were not equipped with any Required Time of Arrival (RTA) capability. However, meter fix RTA advisories, along with cruise speed recommendations, were in many instances up-linked to arriving aircraft.

Procedural Assumptions and Operational Rules

1. Aircraft at or above FL290 were in free flight, with all aircraft below FL290 under positive ATSP control. (The en route DAG-TM concepts call for mixed free maneuvering and ATSP managed aircraft up to the TRACON boundary. The use of the altitude boundary and uniform equipage represented an interim developmental stage toward the mature concepts.)
2. All aircraft had to be cleared by the ATSP to enter or exit free flight airspace.
3. The ATSP could cancel free flight operation at any time.
4. Only one party (FC or ATSP) was responsible for separation at any time.
5. The ATSP had sole authority to cancel self-separation (free flight).
6. The FC, upon acceptance, was responsible for separation assurance.
7. The FC could request ATSP assistance for conflict resolution, flow control, and air traffic management/route considerations.

8. The FC could request the cancellation of free flight.
9. The ATSP provided RTA advisories for a metering fix for free flight aircraft. However, the FC was responsible for separation and meeting the RTA clearance while above FL290.
10. Below FL290, the ATSP was responsible for separation and meeting the meter fix arrival times.
11. The FC could request a flight plan change at any time.
12. The ATSP was instructed to consider user preferences whenever possible.
13. In terminal airspace, the FC received a clearance to maintain a spacing interval behind a lead aircraft. The responsibility for aircraft safe separation remained with the ATSP. However, the ATSP could revoke the self-spacing clearance at any time.

Roles and Responsibilities–En Route Airspace

Controller

In CE 5 scenarios, the ATSP's role involved providing a DST-generated, four-dimensional flight profile for the transition phase from en route cruise altitude to the arrival fix, monitoring sector traffic, and assisting aircraft with weather and ride information. In the transition airspace, the controller ended the free flight status for arriving aircraft, reinstated positive control, and prepared each flight for sequencing and hand-off to the TRACON ATSP. In CE 6 scenarios, the ATSP's role included providing a flight profile for the transition phase from en route cruise altitude to the arrival fix, monitoring sector traffic, and either approving or disapproving proposed route change requests from aircraft. The controller was responsible for aircraft safe separation in CE 6 trials.

Flight Crew

The FC role involved using the CDTI for route management, navigation, and detection and resolution of conflicts. Each aircraft broadcast its route and any route changes to proximal traffic and to the ATSP. In the CE 5 scenario, the FC was not required to obtain prior approval from the ATSP for a route change. However, once free flight was terminated in the transition airspace, the aircraft returned to the positive control of the ATSP. In the CE 6 scenario, prior ATC approval to implement a route change was required.

The CDTI presented a conflict alert to the FC when detected (see Figure 1). The Route Assessment Tool (RAT) (a part of the CDTI) was used to develop a conflict-free path around the conflicting aircraft.

Roles and Responsibilities–Terminal Airspace

Controller

The en route ATSP delivered aircraft to a fix at the TRACON boundary. The TRACON ATSP's role required clearing aircraft to follow a customized FMS approach transition to the runway. The ATSP used spacing matrix derived intervals, typically 70 to 110 seconds, for in-trail approach spacing.

Flight Crew

The FC's role required using the CDTI in spacing mode to maintain the ATSP assigned in-trail position relative to the designated lead aircraft, through descent to the final approach fix.

Research Environment and Equipment

Creating the research infrastructure to conduct DAG-TM research was one of the early objectives, and a focus of this demonstration. Expanding the research environment to incorporate additional participant pilots (including aircraft simulators at NASA Langley) and AOC operations is a future goal.

Air Traffic Control Equipment

The Center TRACON Automation System (CTAS) in the NASA Ames Airspace Operations Laboratory provided ATSP automation tools for planning and controlling air traffic. [7] CTAS generated air traffic advisories designed to increase fuel efficiency, reduce delays, and provided automation assistance to air traffic controllers in achieving acceptable aircraft sequencing and separation, as well as improved airport capacity.

Flight Deck Equipment

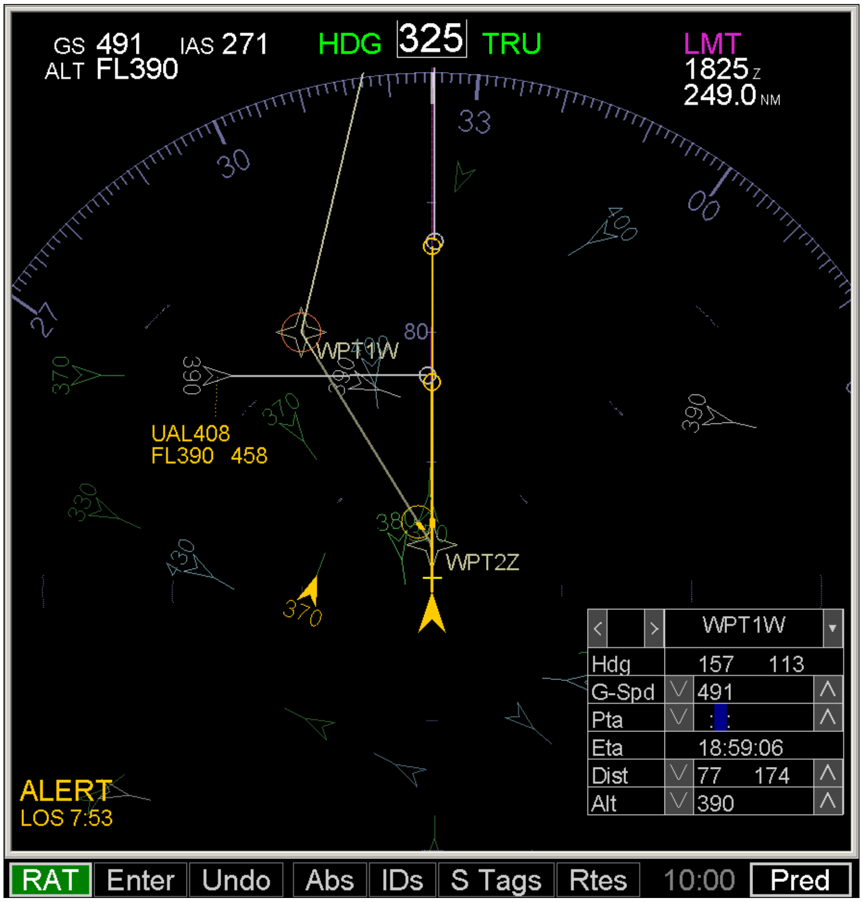
The ACFS was configured as a generic commercial passenger aircraft, equipped with an array of advanced flight deck tools including touch-sensitive screens, a heads-up display, and pitch/roll axis sidesticks. Figure 2 shows the ACFS flight deck, CDTI displays, and outside view (at touchdown).

Cockpit Display of Traffic Information

The CDTIs (one each for the captain and first officer) installed in the ACFS displayed proximal aircraft. Conflict detection and alerting were enabled, using probabilistic algorithms and a look-ahead time based on an ADS-B range of 120 nm. The RAT was available to the FC for the planning and execution of route modifications to avoid conflicts in free flight, and for route modifications designed to provide for increased efficiency and/or the meeting of traffic flow management constraints. The CDTI also incorporated new features designed specifically for the demonstration. These included the following:

1. Route down-linking to ATC (information-only in free flight) and receipt of up-linked ATC routes for FC consideration/implementation.
2. An in-trail approach spacing algorithm with associated display elements, and manual or auto-throttle control-loop options.

Figure 1. CDTI Displaying a conflict alert and use of the Route Assessment Tool (RAT)



Flight Deck Display Research Laboratory

Two single-pilot simulator stations, each equipped with PC-Plane (see Figure 3) and a CDTI display, were used in this laboratory. For the concept demonstration, a confederate pilot operated each of these stations.

Data Collection

As the activities undertaken were a technology and concept demonstration only; data analysis was limited to questionnaires and debriefings. Participant pilots and controllers completed questionnaires after each scenario run, and at the conclusion of the demonstration as a whole. The questionnaires addressed issues related to usability, workload, situation awareness, information needs, DSTs, and the procedures used during the CE 5/11 and CE 6/11 scenarios.

Results and Discussion

The results presented here are based on the collected questionnaire and debriefing data, and are categorized into procedural considerations, usability of the DSTs, and human performance issues. The comments noted below are based on a very limited participant pool, are largely anecdotal as a consequence, and therefore limited in scope.

Figure 2. Advanced Concepts Flight Simulator with Cockpit Display of Traffic Information left and right of center pedestal.

Figure 3. PCPlane Interface on touch screen in Flight Deck Display Research Lab.

<u>Procedural Considerations–Ground Side</u>
Several issues were identified, including:

1. The procedures for holding aircraft in free flight airspace (for example, due to traffic congestion in the terminal environment) need to be addressed.
2. The controller may not be actively controlling aircraft in free flight airspace, thereby possibly only monitoring, with reduced situation awareness. In such a situation, it may be difficult for the controller to take over aircraft separation responsibilities (e.g., at short notice; or in an emergency). Therefore, consideration must be given to maintaining controller situation awareness.
3. There should be cues on pilot and controller displays to indicate when an aircraft is in free flight, transition, or controlled airspace.
4. Since CE 11 self-spacing operations require that pilots change speeds to maintain specified spacing behind an aircraft, the pilots should be allowed to deviate from present charted approaches as necessary.
5. During a self-spacing operation, it is important to predict when a potential separation loss will occur, therefore controller tools and alerts will be needed to support an awareness of this potential problem. CE 11 self-spacing procedures need to be expanded to encompass off-nominal circumstances.
6. In CE 5 operations, ATSP participants reported a dislike of the concept of mixed control in free flight airspace. In one case, confusion over separation responsibility resulted from an arrival aircraft that requested a descent while still in free flight.
7. Further work is needed on procedures for transitioning from free flight to controlled airspace.

<u>Procedural Considerations – Air Side</u>
The following air side procedural considerations were derived from pilot comments:

1. An overall comment from the pilot participants was the need to clarify pilot flying (PF) and pilot not flying (PNF) responsibilities for both CE 5 and CE 6 operations. An increase in DST use such as the spacing aid on the CDTI may increase the need to clearly distribute responsibilities within the cockpit. One suggestion was that the PF monitors aircraft and communicates with the ATSP, while the PNF executes route changes and spacing entries.
2. For CE 6 operations, pilots preferred not to advise ATSP of a problem being solved. Instead they suggested that they resolve the conflict and then inform the ATSP of resolution via datalink.
3. Pilots expressed a desire to receive a descent clearance either before or as soon as ATSP takes positive control. Pilots also suggested allowing aircraft to begin the arrival descent while in free flight, prior to ATSP positive control. (The en route DAG-TM concept eventually calls for free flight all the way to the TRACON boundary.)
4. Pilots reported that they assumed they were in free flight until they received an ATSP cancellation.
5. The pilots indicated that they preferred to have a verbal and/or displayed indication of "free flight cancelled" (or ATSP positive control being resumed).
6. Interestingly, the pilots were split in their preference for CE 5 or CE 6 operations. One pilot preferred CE 5 because of less interaction with the ATSP and more freedom for changes. The other pilot preferred to rely on the ATSP's expertise in separating aircraft.

Overall, pilots reported that CE 11 self-spacing operations were successful and they could follow an ATSP assigned time interval. For CE 5, CE 6, and CE 11 operations, pilots suggested the following changes to the FMS:

1. Display a fix time in hrs:mn:sec on the progress of route data.
2. Display a SEND button for route change requests. These may be sent to the ATSP and then the ATSP sends a datalink approval and loads the route into the ATC DST. The pilot would then execute the new route indicating cockpit agreement.

CDTI Usability

The following feedback was obtained about the CDTI. These comments should be taken as indicative rather than conclusive due to the small sample size.

CE 5 and CE 6 Operations

1. Minimal effort was required to display surrounding traffic and to detect conflicts.
2. Conflict detection was possible even before an alert was presented for CE 5 operations, whereas it was more difficult in CE 6 operations. This finding was expected because of the difference in alert time between flight deck and ATC conflict detection algorithms, and the changes in roles and responsibilities. In CE 6 scenarios, controllers reported that they solved most if not all conflicts as soon as they became apparent. Thus in CE-6 flight crews were exposed to very few conflicts.
3. The conflict alerts provided adequate time for maneuvering.
4. The workload involved to detect and resolve conflicts was acceptable.
5. The CDTI was found to enhance traffic situation awareness, and was an essential component for free maneuvering.

CE 11 Operations

1. The CDTI aided the determination of spacing from the lead aircraft.
2. Minimal effort was required to use the "target box" to keep adequate spacing from the lead aircraft.
3. The selected target feature was used to identify other traffic or traffic to follow.

Interface Considerations

The colors used to code the traffic symbols were appropriate and found to be consistent with other flight deck displays. Symbology was familiar because it was similar to the Traffic Collision and Avoidance System (TCAS), and was as useful or better than TCAS. Some problematic issues were identified, including difficulty with color discrimination, difference in the thickness of the lateral route lines, and disappearance of the heading track after 10 sec.

Overall CDTI Characteristics

The general feedback about the tool, in spite of a few recommended changes, was that it was an excellent aid for conflict detection and resolution in the en route, free flight phase, as well as in the controlled flight phase. Pilots also indicated that the CDTI was a useful aid for self-spacing and a good situation awareness tool.

The additional design recommendations included having vivid and bolder colors, and reducing button presses for datalink messages. Also, a suggestion was made to change traffic symbols to white. Operational recommendations included making altitude change the same as speed change and making a flight level change available on the flight director and point of approach.

Human Performance Considerations

Both the controllers and the pilots provided ratings of physical workload, mental workload, overall workload, and situation awareness on a five-point interval scale (1 = very low, 3 = medium, and 5 = very high). The physical workload received moderate ratings from both the controllers and the pilots under all conditions. For controllers, as expected, CE 5 Heavy and CE 6 Heavy had higher physical, mental, and overall workload ratings than CE 5 Light, likely due simply to the higher traffic levels present.

For pilots, the CE 5 Heavy condition had lower physical, mental, and overall workload than CE 5 Light. This is interesting and perhaps could be attributed to a learning effect since the CE 5 Heavy scenario was only completed after CE 5 Light. Alternatively, traffic density may not have the same effect on FC workload as it does on the ATSP. As expected, CE 6 Heavy resulted in a higher pilot physical, mental, and overall workload as compared with CE 5 Heavy. This higher workload was attributed to increased communications with controllers for trajectory negotiation and intent information.

Situation awareness was moderate or higher for both controllers and pilots in all conditions.

Figures 4 and 5 illustrate the controller and pilot average ratings of the measures under all the conditions.

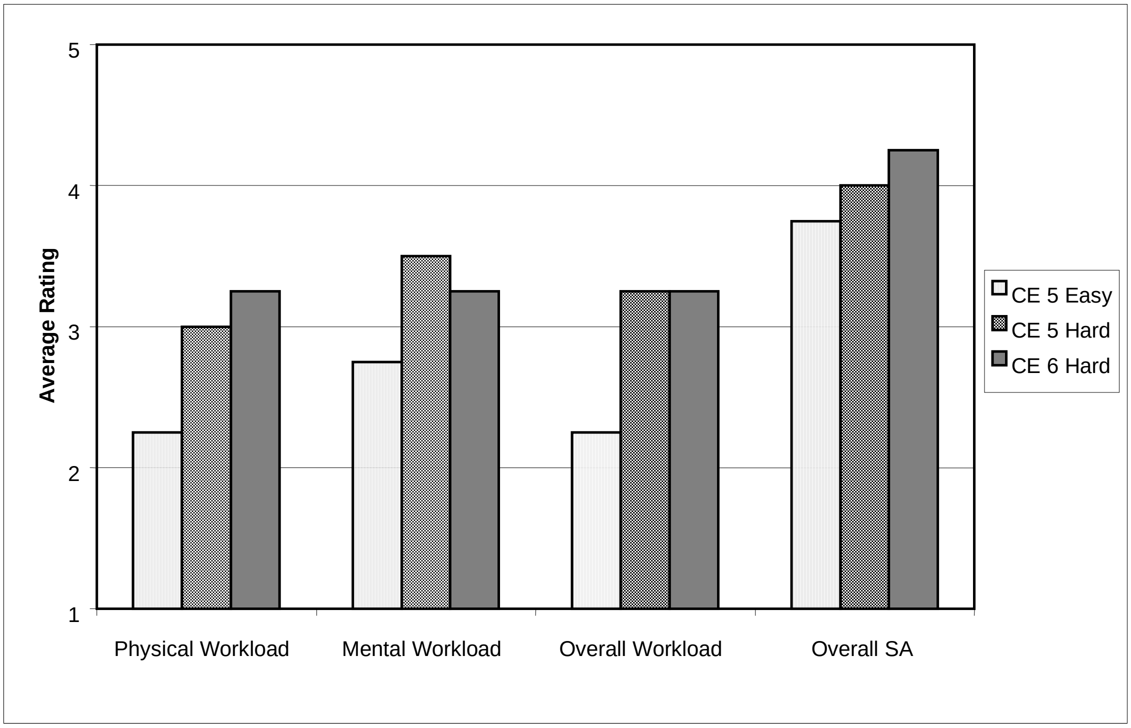


Figure 4. Average Controller Workload and Situation Awareness Ratings.

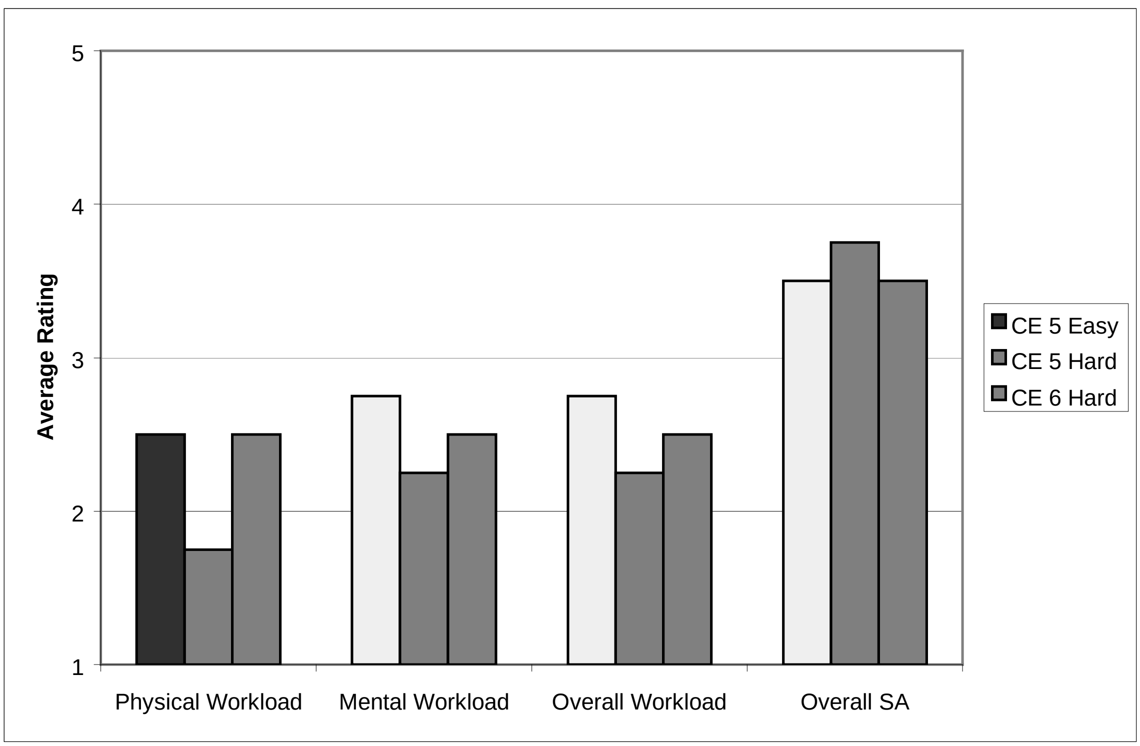


Figure 5. Average Pilot Workload and Situation Awareness Ratings.

Conclusions

Overall, we considered the initial technology and concept demonstration to have been a success. In summary:

1. The NASA Ames DAG-TM team successfully developed a physical and technical infrastructure to conduct ongoing DAG-TM research.
2. The demonstration was based on a *build a little, test a little, demonstrate a little* principle. This proved beneficial as procedural and DST characteristics were iteratively improved during preparation for the demonstration.
3. The feedback from controller participants reinforced the need to conduct further research related to procedures.
4. Both the controllers and pilots indicated that on-screen cues that distinguish free maneuvering, transitioning, and self-spacing aircraft are needed.
5. The CDTI and CTAS DSTs were helpful and supported the CE 5, CE 6, and CE 11 operations. Various DST features need further refinement.
6. Controller and pilot comments indicated the concepts to be feasible.

This demonstration did not include a baseline(control test condition), or a true variety of traffic flows and weather conditions, and used a minimal participant pool. The findings must, therefore, be interpreted with caution by the reader. Primarily, the study demonstrated the technological capabilities, information displays, and basic procedures that support the concepts, rather than the systematic assessment of their benefits.

Further Research

The participant feedback and DAG-TM team observations indicated that further research is needed to address the following:

1. Complex traffic conditions that include a mix of overflights, transitioning aircraft, arrivals and departures.
2. Different airspace configurations for aircraft transitioning between free flight and controlled airspace.
3. More realistic conflicts that include conflicts spread throughout the scenario, conflicts involving more than two aircraft, simultaneous conflicts, and successive conflicts for the same aircraft.
4. More realistic trajectory negotiation processes where the ATSP and FC iteratively develop mutually agreeable route changes;
5. Inclusion of weather and special use airspace that will constrain aircraft routes.
6. Consideration of airline priorities, and AOC involvement in required time of arrival sequencing and route changes.
7. Different aircraft equipment mix with CDTI and non-CDTI equipped aircraft.

Future studies in collaboration with NASA Langley are slated to gather comprehensive data addressing operational feasibility and concept benefits

References

1. Advanced Air Transportation Technologies (AATT) Office. (1999). *Concept Definition for Distributed Air/Ground Traffic Management* (DAG-TM) Version 1.0, Moffett Field, CA: NASA Ames Research Center.
2. Philips, C. T. (2000). *Detailed Description for CE-5: En route free maneuvering* (NAS2-98005 RTO-41). Billerica, MA: Titan Systems Corporation.
3. Couluris, G. J. (2001). *Detailed Description for CE-6 En Route Trajectory Negotiation.* (Contractor Report NAS2-98005 RTO-41). Los Gatos, CA: Seagull Technology, Inc.
4. Sorensen, J. A. (2000). *Detailed description for CE11. Terminal arrival: Self-spacing for merging and in-trail separation* (NAS2-98005 RTO-41). Los Gatos, CA: Seagull Technology, Inc.
5. Johnson, W.W., Battiste, V., and Holland, S. (1999). *A Cockpit Display Designed to Enable Limited Flight Deck Separation Responsibility.* Proceeding of the 1999 World Aviation Conference, Anaheim, CA.
6. Abbott, T. S. (2002). *Speed Control Law for Precision Terminal Area In-Trail Self-Spacing*, (NASA/TM-2002-211742).
7. Sanford, B. D., Smith, N., Lee, K., & Green, S. (1999). *Decision-aiding Automation for the En Route Controller: A Human Factors Field Evaluation*. Presented at the Tenth International Symposium on Aviation Psychology. Columbus, OH.